The Formation of Natural and Artificial Rain

BY

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IAN ASSOCIATION FOR THE CULTIVATION OF SCIENCE

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I—NATURAL RAIN

Introduction

The mechanism by which rain forms has been the subject of discussion among meteorologists for a very long time and it cannot be said that there is any unanimity of opinion on the exact physical processes by which raindrops form and fall to the ground. As an example of the differences in points of view, Bergeron[1] in 1933 postulated that "almost every real raindrop (d $>$ 0.5 mm.) . . . originated around an ice crystal". Simpson[2], on the other hand, quotes Indian meteorologists as being of the opinion that rain frequently falls from clouds which do not reach to freezing level and therefore could not have formed in the manner described by Bergeron ; while in the Hawaiian Islands, some parts of which receive an annual rainfall of 200 or 300 inches, there is good reason to believe that practically the whole of it results from non-freezing clouds.

The unsatisfactory state of ideas on rain formation is largely due to the difficulty of investigating what goes on inside clouds. In recent years, however, a new tool for the investigation of rain formation has become available in the form of centimetre-wave radar sets. It is well known that such sets operating on wavelengths of 3 or 10 centimetres, while incapable of receiving echoes from the tiny droplets which make up the majority of clouds, can detect the radiation scattered from raindrops and from snow or ice particles.

Using radar sets of this type, a great deal of new information has been obtained about the mechanism of rain formation, and there has been a rapid improvement in our understanding of the physical processes involved. The method is particularly powerful if the radar set is installed in an aircraft which can investigate the phenomena at close quarters.

Broadly speaking, it has been found that, following the formation of clouds by condensation, there are at least two processes which might lead them to produce rain. The first of these is that postulated by Bergeron, in which rapid growth follows the appearance of ice crystals in the top of a cloud. The other process is the coalescence of small cloud droplets to form big drops, the clearest examples of which take place in clouds which are wholly at temperatures above the freezing level.

It is proposed in the present paper to treat each of these processes in turn, and to describe some radar and aircraft observations which have contributed to their understanding.

Bergeron-type Rain

If rain falling from clouds which extend well above freezing level is observed by radar, a very characteristic echo pattern is often seen, as shown in Plate I. This type of picture is obtained on a conventional 10-centimetre PPI-type radar in which the beam is made to rotate continuously about a horizontal instead of a vertical axis. A picture is then obtained which is a vertical cross-section through the rain area, the point of observation being in the centre of the base line. The radar echo extends downwards from about 15,000 feet and there is a marked intensification at 10,000 feet. This frequently occurs a few hundred feet below the freezing level in the atmosphere, and Ryde[3] suggested that it was due to the increased reflecting power of snowflakes or ice crystals when they become wet at the instant of melting.

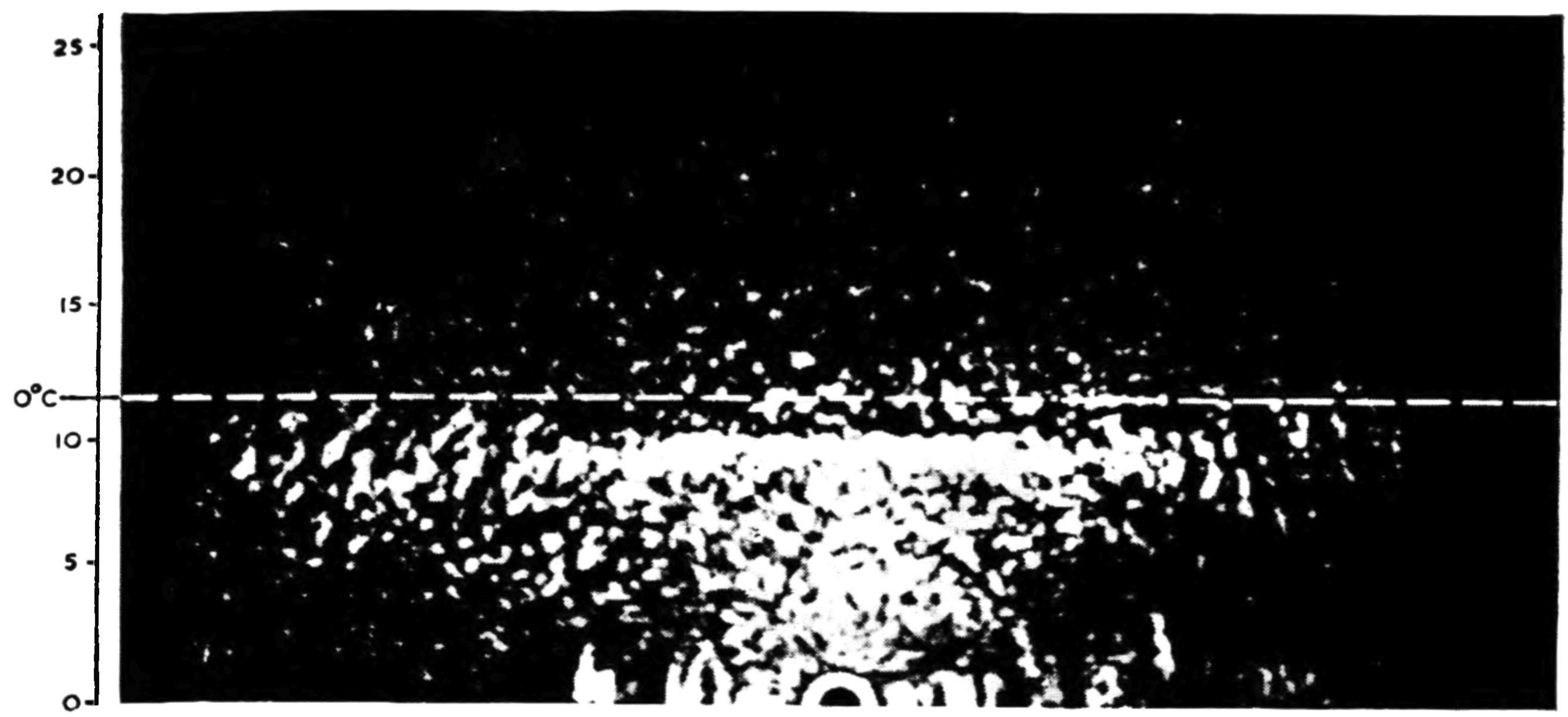
This hypothesis has been investigated experimentally with radar-equipped aircraft flying at different levels through cloud which was producing precipitation in this way. A typical example occurred in south-east Australia on the afternoon of March 6, 1950. Drizzle was falling from a widespread layer of alto-cumulus, the base of which was at 10,500 feet and the top at 18,000 feet ; the freezing level was at 12,000 feet. Over a period of several hours the aircraft flew through the cloud at a variety of heights. Radar patterns obtained on the aircraft radar are shown in Plates IIa, IIb and IIc, in which the aircraft was respectively above, at the same level as, and below the intense radar band. This band was centred at 11,000 feet where the temperature was $+\frac{1}{2}$°C.

Above the band it was found that the cloud consisted of a mixture of ice needles and supercooled droplets. Below the band there was light rain, the raindrops, estimated from those hitting the windscreen, to be $\frac{1}{4}$ to $\frac{1}{2}$ mm in diameter. The band itself coincided with the boundary above which were ice crystals and below which were raindrops. This is one of many occasions on which the same phenomenon has been observed and it provides direct confirmation of the fact that rain was forming by the Bergeron process. It also confirms Ryde's suggestion that the intensification of the radar echo just below freezing level is due to the melting of the ice particles.

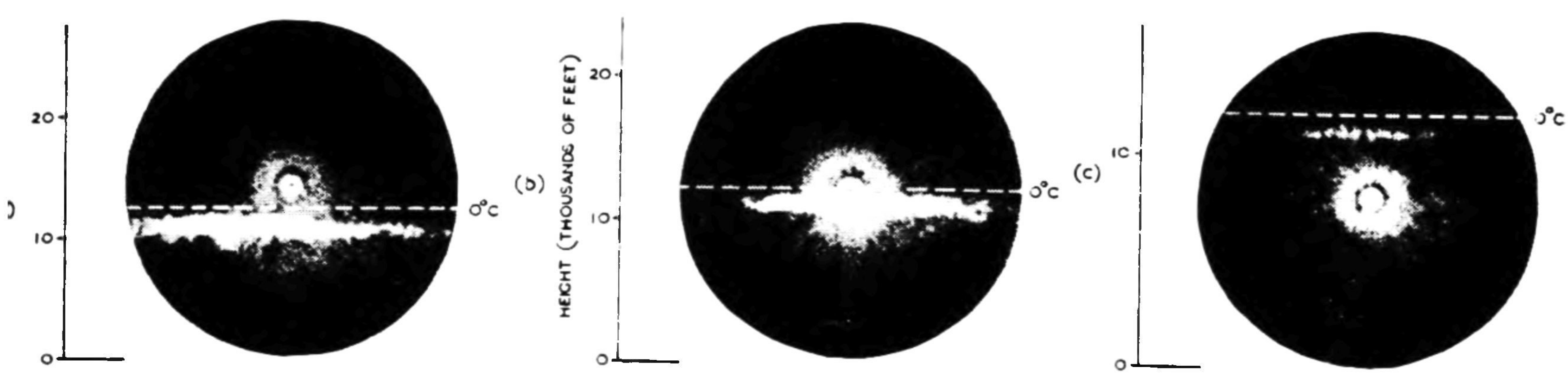
The region from which the intense radar echo is obtained has previously been referred to as the "radar bright band". In view of the fact that it is invariably connected with the melting process, and in order to distinguish it from other band structures which will be described shortly, it is proposed that it should in future be called the *melting band.*

Upper Radar Bands

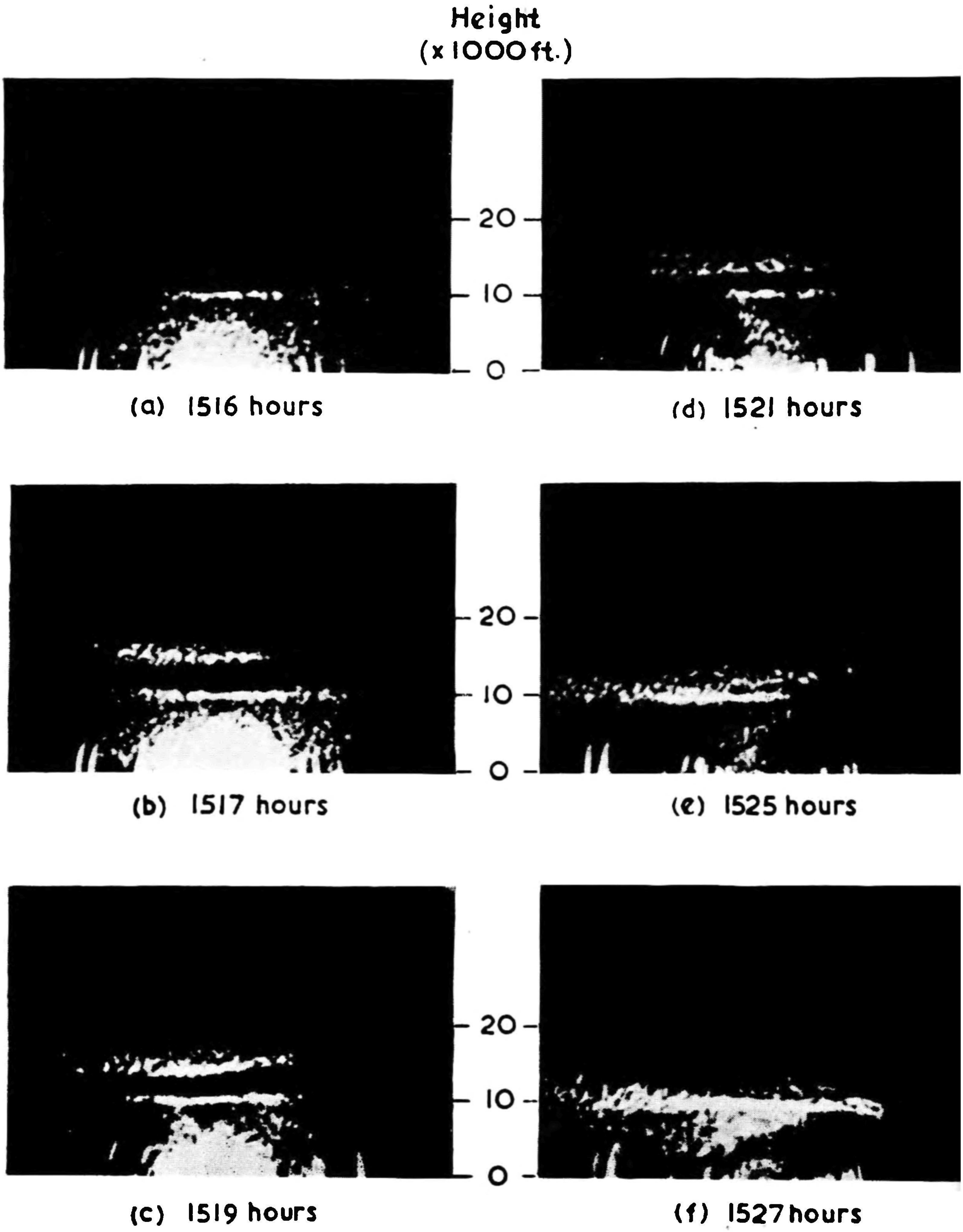
On many occasions when rain forms by the Bergeron process the radar echo pattern appears as in Plate I for many hours at a time. On other occasions, however, somewhat different conditions exist and other radar bands may form



I. Echo pattern as observed by radar in Bergeron-type rain.



II. Radar patterns obtained on the aircraft radar.



III. A sequence of ground radar pictures taken at intervals of approximately 2 minutes.

at considerably greater heights in the atmosphere. These are sometimes of a transient nature and sometimes remain more or less stationary at one height. More often, however, they fall steadily towards the freezing level and merge with the melting band.

A typical example occurred in Sydney on the afternoon of October 24, 1949, when a complex low-pressure area covered New South Wales. Light rain fell from 14-00 to 21-00 hours Eastern Standard Time, radar observations being made from 14-30 hours onwards. There was a melting band at 10,000 feet, and at 15-15 hours an upper band formed at 16,000 feet. This grew rapidly in intensity and fell towards the melting band. A sequence of ground radar pictures taken at intervals of aproximately two minutes is given in Plate III. When it reached the melting band at 15-27 hours this band itself increased markedly in intensity, as is clearly shown in Plate III(f). At 15-35 hours the upper band reformed and the process was repeated.

This example is typical of a number of upper band structures which have since been observed in some detail. The general characteristics of the upper band which may be deduced from these observations are as follows :

(*a*) The upper band usually forms as a horizontal or nearly horizontal layer in the atmosphere and then falls until it merges with the melting band. When it reaches the melting band the latter shows a marked increase in intensity. The upper band tends to form again and repeat the process after an interval of from 20 to 30 minutes.

(*b*) Upper bands may form over a wide range of heights in the atmosphere. The air temperatures where the band forms are remarkably consistent and are distributed around the figure of $-15°$C., which is frequently quoted as the temperature at which glaciation is seen to occur visually in clouds.

(*c*) The bands sometimes remain stationary at one height, but in the majority of cases they fall towards the melting band. On these occasions the rate of fall may vary between 4 and 8 feet per second. This is of the same order as or slightly higher than the known rate of fall of ice crystals and snowflakes in the atmosphere.

The most obvious explanation of the upper bands is that they are associated with the appearance of ice crystals near the level at which they are first detected. Their subsequent behaviour is consistent with the growth in size of the particles, their fall and subsequent melting around the 0° isotherm.

The formation of the ice crystals could be due either to sublimation direct from the vapour phase, or to the freezing of water droplets. A considerable body of experimental evidence, which was reviewed recently by Dobson,[4] shows that sublimation is unlikely to occur at all readily until temperatures of —30° or —40°C. are attained. It is unlikely therefore that the formation of the upper bands is due to sublimation. Furthermore, the probability of ice crystals forming by this process varies only slowly with temperature and there is no reason to expect a band to appear suddenly at a discrete height.

Laboratory experiments by Heverly[5] show, on the other hand, that while small cloud droplets do not freeze spontaneously until they reach similar temperatures of —30° or —40°C., larger drops freeze at gradually increasing temperatures, the larger sizes all tending to freeze at temperatures distributed about —16°C. These results have since been verified by Dorsch and Hacker[6]. The curve of spontaneous freezing temperature against drop size given by them is reproduced in Figure 1.

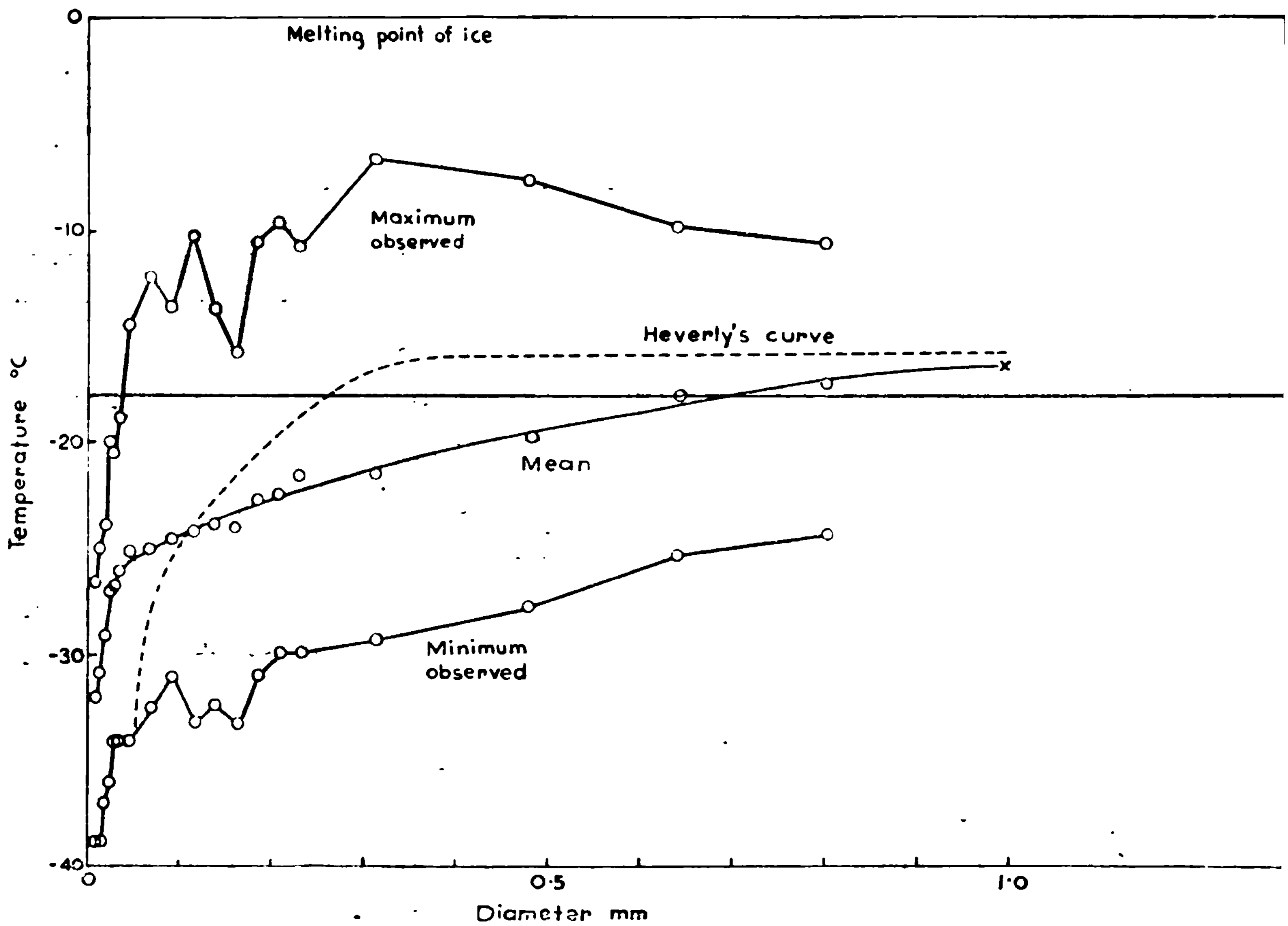


Fig. 1. Experimental observations of Dorsch and Hacker, and of Heverley, on the spontaneous freezing temperature of drops of different diameters.

The agreement between the temperature at which large drops freeze spontaneously and that at which upper radar bands form in the atmosphere is significant and suggests that the bands are due to the spontaneous freezing of water drops. Shortly after freezing they would grow rapidly in the manner postulated by Bergeron and their reflectivity, being proportional to the sixth power of the linear dimensions, would increase very rapidly. They would therefore be expected to become visible on a radar set soon after freezing occurs.

There is ample evidence to show that drops of the required size often exist in the upper regions of deep clouds. E. J. Smith[7] has given an example of drop spectra in the top of a cloud in which the mean diameter of the drops was 0.3mm. and a considerable fraction was larger. Other examples have been given by Jones[8] in which drops of still greater size have been found in the supercooled state at heights above the freezing level. It is difficult to account for such drops by the condensation process and it will be shown later that they probably form by coalescence of cloud droplets in the ascending air current. Quite large drops can be transported upwards by this means, and on crossing the freezing level they would remain in a supercooled state for some considerable time. If Heverly's results apply to drops in the atmosphere they would tend to freeze spontaneously, however, at temperatures distributed about −16°C.

It may therefore be concluded that the mechanism giving rise to the appearance of upper band structures is the spontaneous freezing of large drops which have formed in the cloud. On freezing these would grow rapidly at the expense of the surrounding water drops and fall to the 0° isotherm, where they would melt and fall as rain. This process is contrary to the ideas of Findeisen[9], who was of the opinion that the initial appearance of ice crystals was due to direct sublimation from the vapour to the solid phase on to sublimation nuclei.

Formation of Rain in Convective Clouds

The layer type of echo described above is not the only type observed by radar. The echo pattern often takes an entirely different form, the most characteristic being a column structure of which that shown on Plate IV is typical. Such echo forms are quite well known and have been described a number of times in the literature. They usually occur in convective clouds, each column being confined to a single cloud cell. They have been observed in Australia :

(*a*) In clouds which are confined to heights entirely below the freezing level and which must therefore consist wholly of water droplets.

(*b*) In clouds which extend a few thousand feet above freezing level.

(*c*) In towering cumulus which reach to heights of 30,000 feet or more in the atmosphere and ultimately become cumulo-nimbus clouds.

All three types have been investigated by aircraft flights and by means of ground and airborne radar and, as described below, the outstanding experimental result is that ice crystals do not appear to play any part in the formation of rain in the case of clouds described under (*a*) and (*b*) above, nor are they necessarily involved, at least in the initial stages, in rain formation from the towering cumulus clouds mentioned under (*c*).

The three types will now be discussed in turn.

(a) Convective clouds wholly warmer than freezing

The clearest examples of rain forming without ice crystals being involved are found in convective clouds, of the so-called non-freezing kind, the whole of which are at a temperature above freezing. Such clouds often occur in warm-temperate and tropical regions and they frequently give copious falls of rain. Several examples of this type of cloud have recently been described[7, 10, 11, 12]. Of necessity, they contain no ice crystals, and in many cases this has been directly confirmed by aircraft flights through them.

One example which may be taken as typical occurred on the afternoon of December 1, 1949, when convective showers fell on the coastal plain and on the mountains west of Sydney, New South Wales. One cloud about 50 miles inland was selected for special study. A temperature sounding made during the ascent gave the curve shown in Plate IV(*a*). The cloud base was at 4,000 feet and the cloud tops generally at 10,500 feet, where the temperature was + 4°C. A few cumulus heads pushed up approximately 1,000 feet higher, but at no time did any clouds in the area reach freezing level, which was at 13,000 feet. When first observed, the top of the cloud selected for observation was at 11,000 feet and it rose steadily during the next hour to a maximum height of 12,500 feet, after which it collapsed to the 10,500 feet level. Flights were made at a variety of heights over the top of the cloud and through the top, and at no time was it found to contain ice particles or snow flakes. When first observed at 14-00 hours the cloud already gave a substantial radar echo reaching to the ground. This persisted with small changes until 14-50 hours, after which it gradually decreased in intensity and disappeared at 15-15 hours. A typical radar photograph is given in Plate IV(*a*) which was taken at 14-27 hours. At this time the aircraft was flying over the top of the cloud at a height of 12,500 feet where the temperature was + 1°C., the top of the cloud being at 12,000 feet where the temperature was + 2°C. ; the top of the radar echo was at 10,000 feet where the temperature was + 4°C.

(b) Convective clouds which extend above freezing level

The example described above is of a convective cloud which built up and produced rain but never attained the height of freezing level. Many convective clouds build up in much the same way, produce rain before reaching the freezing level but continue growing until some part of the cloud top is higher than freezing level.

A typical example occurred on the afternoon of February 23, 1950, when scattered cumulus clouds were building up and decaying over the mountains about 60 miles west of Sydney. The cloud base was at 5,500 feet, and the height of the cloud tops averaged 13,000 feet. Isolated heads occasionally pushed through this level and reached a height of 16,000 or 18,000 feet before dispersing

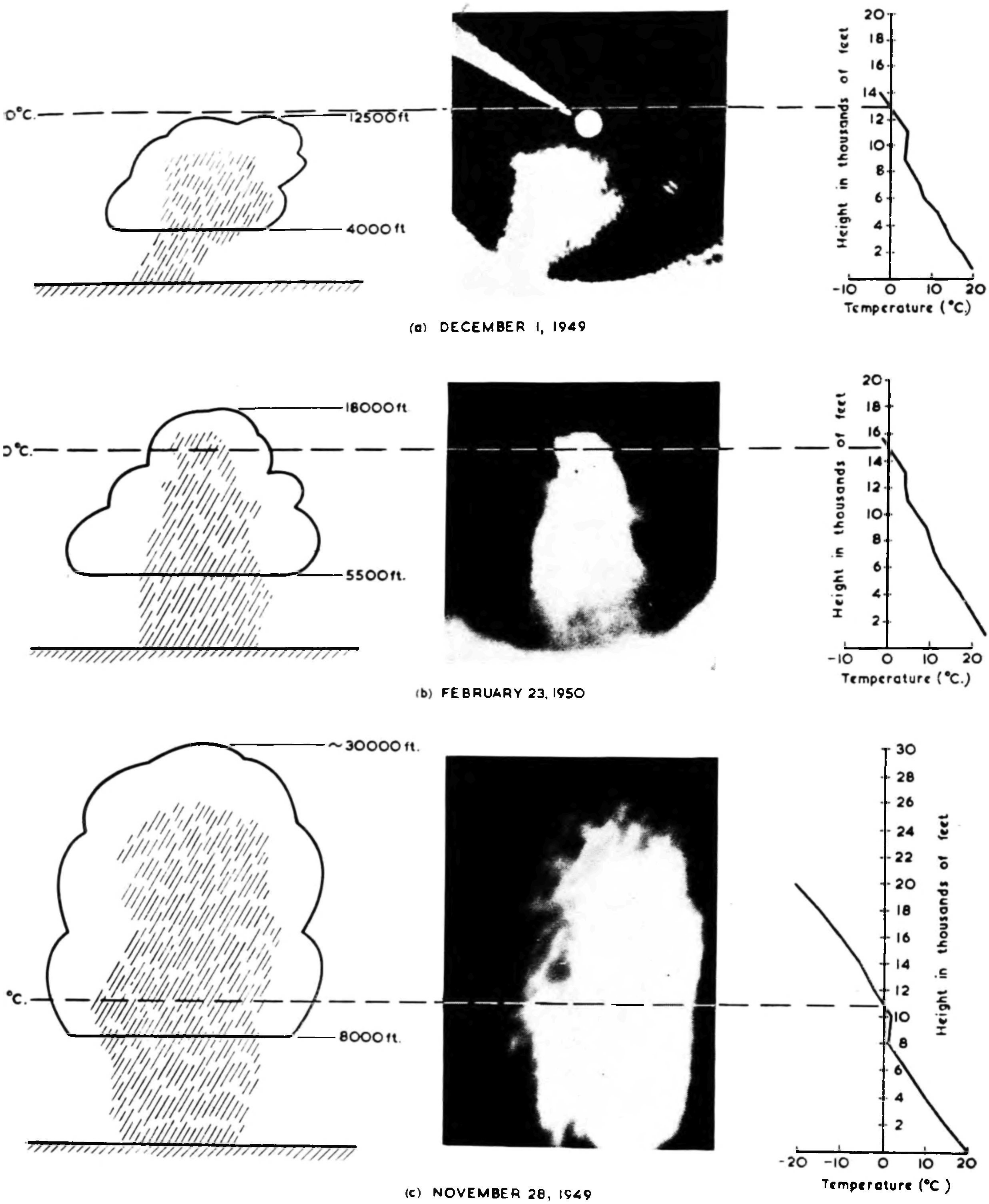
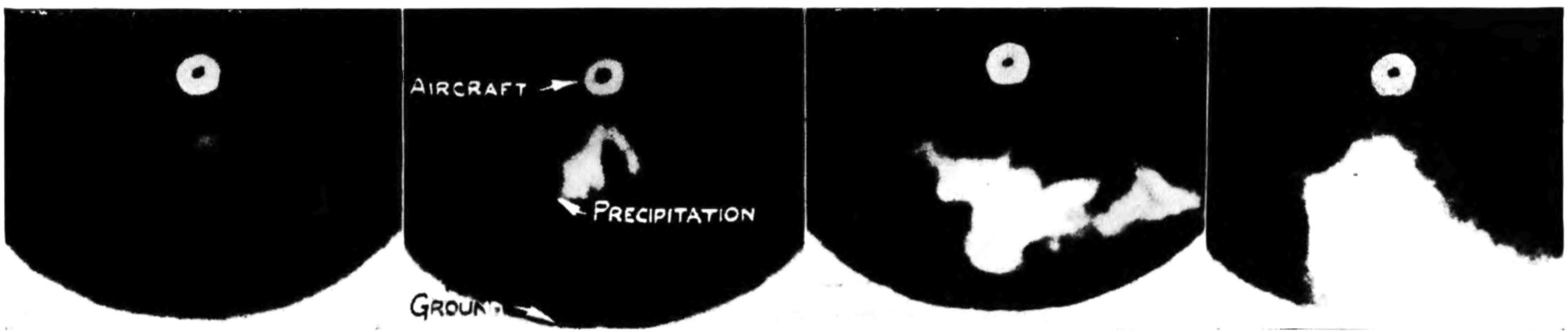


PLATE 4

IV. Column structure of echo observed by radar during the formation of rain in convective clouds.

V. A photograph of the precipitation extending about 50 square miles in a typical dry ice experiment with alto-cumulus cloud.



After 7 minutes | After 10 minutes | After 12 minutes | After 20 minutes

VI. A typical radar record of the growth and fall of precipitation in dry ice experiment.

A temperature sounding made in the clear air during the ascent is given in Plate IV(b), showing that freezing level was at 15,000 feet and a slight inversion existed between 12,000 and 13,000 feet which was probably responsible for limiting most of the cloud to that height. The clear air temperature just above the cloud tops was + 4°C. and at 15-10 hours a radar echo was found to be

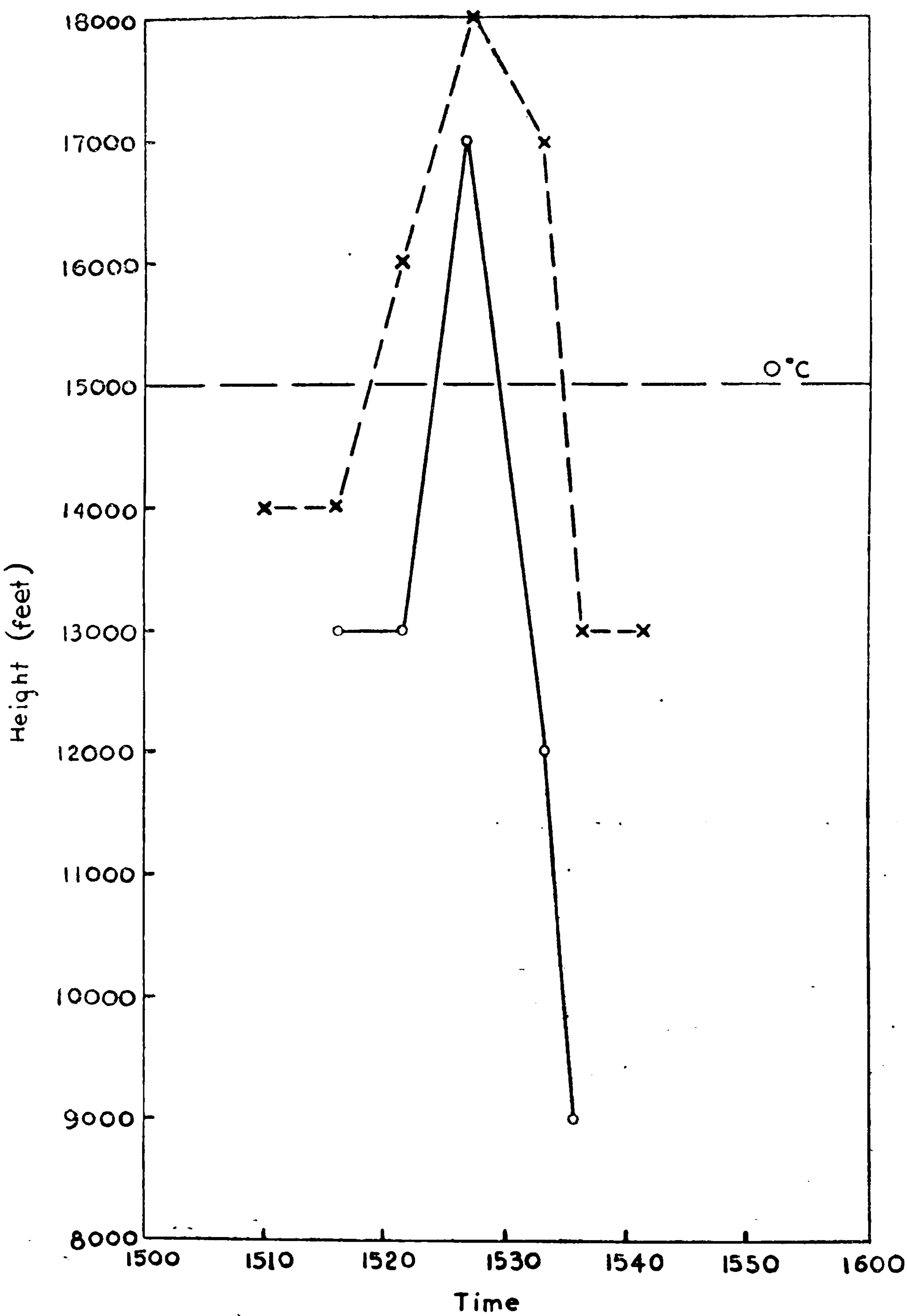


Fig. 2. The variation with time of the height of the top of the cloud and the top of the radar echoes on February 23rd, 1950.

forming beneath a head which projected 1,000 feet above the level of the surrounding clouds.

Thereafter the cloud built up rapidly and reached a maximum height of 18,000 feet at 15-27 hours, after which it began to subside slowly. At 15-35 hours the head suddenly evaporated in the course of a minute. The cloud remained unaffected from 13,000 feet downwards and could be distinguished from its surroundings for some time afterwards.

While these changes were in progress, flights took place through the cloud and over its top, and radar ovservations were made. The radar echo increased in intensity as the cloud built up and the top of the radar echo rose and fell in sympathy with the cloud top. A plot of the height of the top of the cloud against time and of the top of the radar echo is given in Figure 2, showing that, like the cloud, the radar echo started below freezing level, built up above freezing level and then subsided again.

At the time of maximum development of the cloud, the aircraft flew through it at a height of 14,000 feet where the clear air temperature was + 2°C. A strong up draught was encountered and the rain water content was found to be considerable, the whole aircraft being washed by sheets of water. The biggest drop size was estimated to be about 1 mm. and the radar echoes were found to extend to a height of 2,000 feet above the aircraft as shown in Plate IV(*b*).

The results are generally similar to those of December 1, except that in this case both the top of the cloud and the radar echo extended above freezing level at the time of maximum development. It can be concluded that the rain formed by the same process as in non-freezing clouds and that relatively large drops were carried above the freezing level by the up draught in the cloud, both the cloud droplets and the larger drops remaining in the supercooled state.

(*c*) *Towering cumulus which extend to great heights in the atmosphere*

Column-type radar echoes of the kind which have just been described are also observed in towering cumulus clouds which might extend to 30,000 or 40,000 feet in the atmosphere. They have not yet been extensively examined by means of airborne radar equipment but they are often observed on ground radar installations. A typical example occurred on November 28, 1949, when a single isolated cumulus tower was observed west of the Radiophysics Laboratory. It passed a few miles south of the Laboratory and moved off rapidly in an easterly direction. It contained an exceptionally well defined radar echo which persisted for the whole time it was under observation. The tower was first observed at 16-45 hours and a photograph of the radar echo taken at 17-08 is given in Plate IV(*c*). The top of the radar echo extended to some 25,000 feet and the top of the cloud was estimated to be 30,000 feet at that time. Exceedingly heavy rain was falling from the cloud from the time it was first observed—a member of the Laboratory staff drove through the rain area and reported exceedingly heavy rain with hailstones up to ½ inch in diameter. The top of the cloud was obscured by low cloud during the first part of the observation but it came clearly into view at 17-00 hours. It was perfectly rounded as in a cloud consisting entirely of water drops, and there was no sign of glaciation until 17-15 hours, that is, until it had already been raining heavily for at least 30 minutes. Between 17-15 and 17-20 the cloud acquired a distinct icy crown, and at 17-45 there was a fully developed anvil stretching in an easterly direction. A lightning discharge took place between the base of the cloud and the ground at 18-00 hours and the storm continued to be active for some time afterwards.

Before the icy crown appeared the cloud passed over Mascot Airport where a total of .33 inches of rain was recorded in less than one hour.

Although no aircraft observations were made in this case, it is reasonably certain

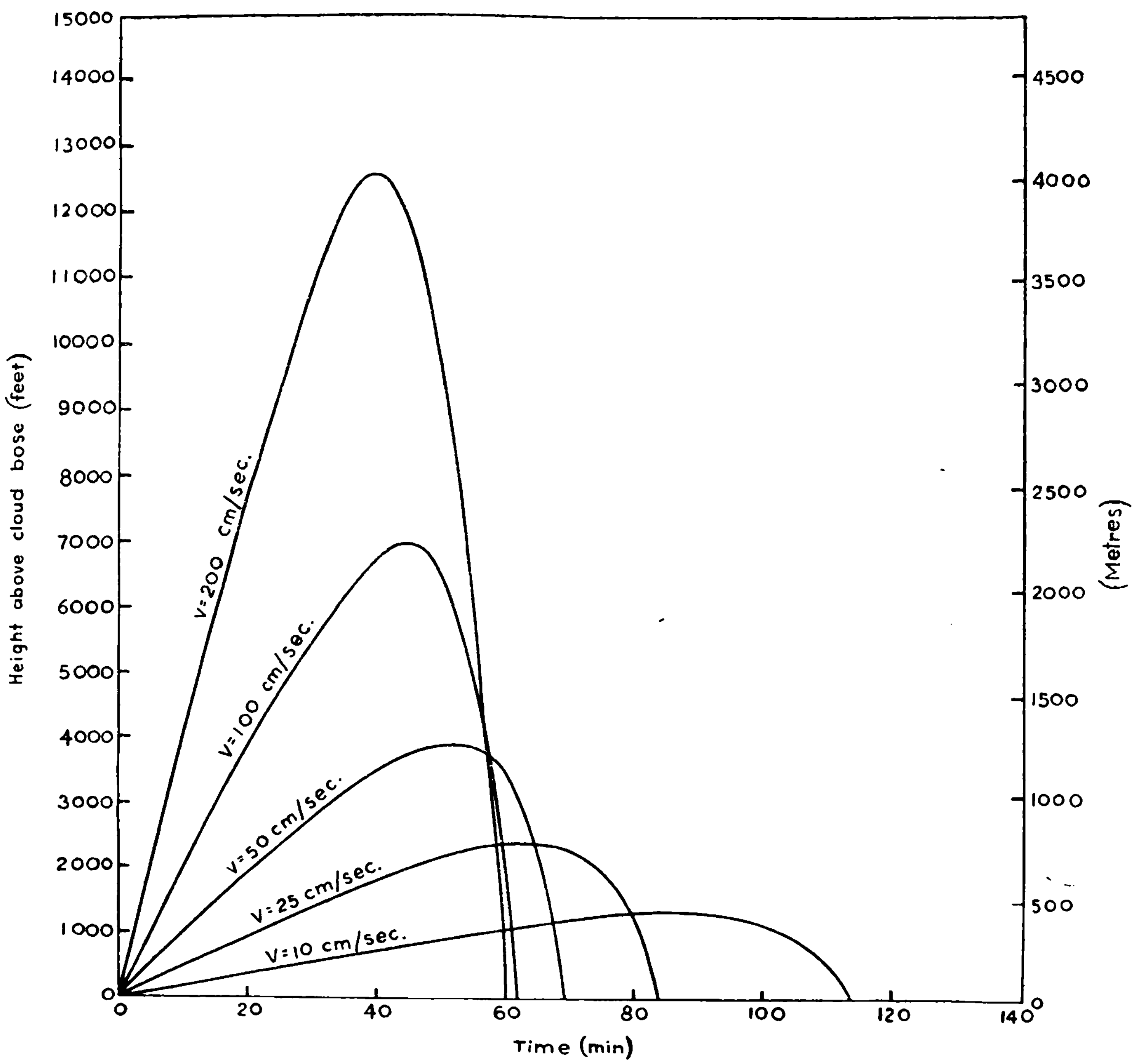


Fig. 3. The trajectories of drops which grow by coalescence in a cloud with a cloud water content of 1 gr. per cu. metre, an average droplet diameter of 20μ and a range of vertical air velocities from 10 to 200 cms/sec.

that heavy rain was falling before the top of the cloud became glaciated. Furthermore there was no sign of a discontinuity in the radar echo intensity near freezing level as is characteristic of clouds which contain ice or snow particles. It is reasonable to suppose, therefore, that the early stages of rain formation were similar to those of December 1 and February 23.

Jones has reported cases in which aircraft have flown through such towers at a height of 6,000 feet above freezing level and encountered predominantly raindrops and occasionally hail. It is tolerably certain therefore that, whatever the mechanism by which the raindrops form in these clouds in the first instance, there is clear evidence of large drops having been transported upward above freezing level.

Discussion of Results

The examples just described have a number of characteristics in common. The

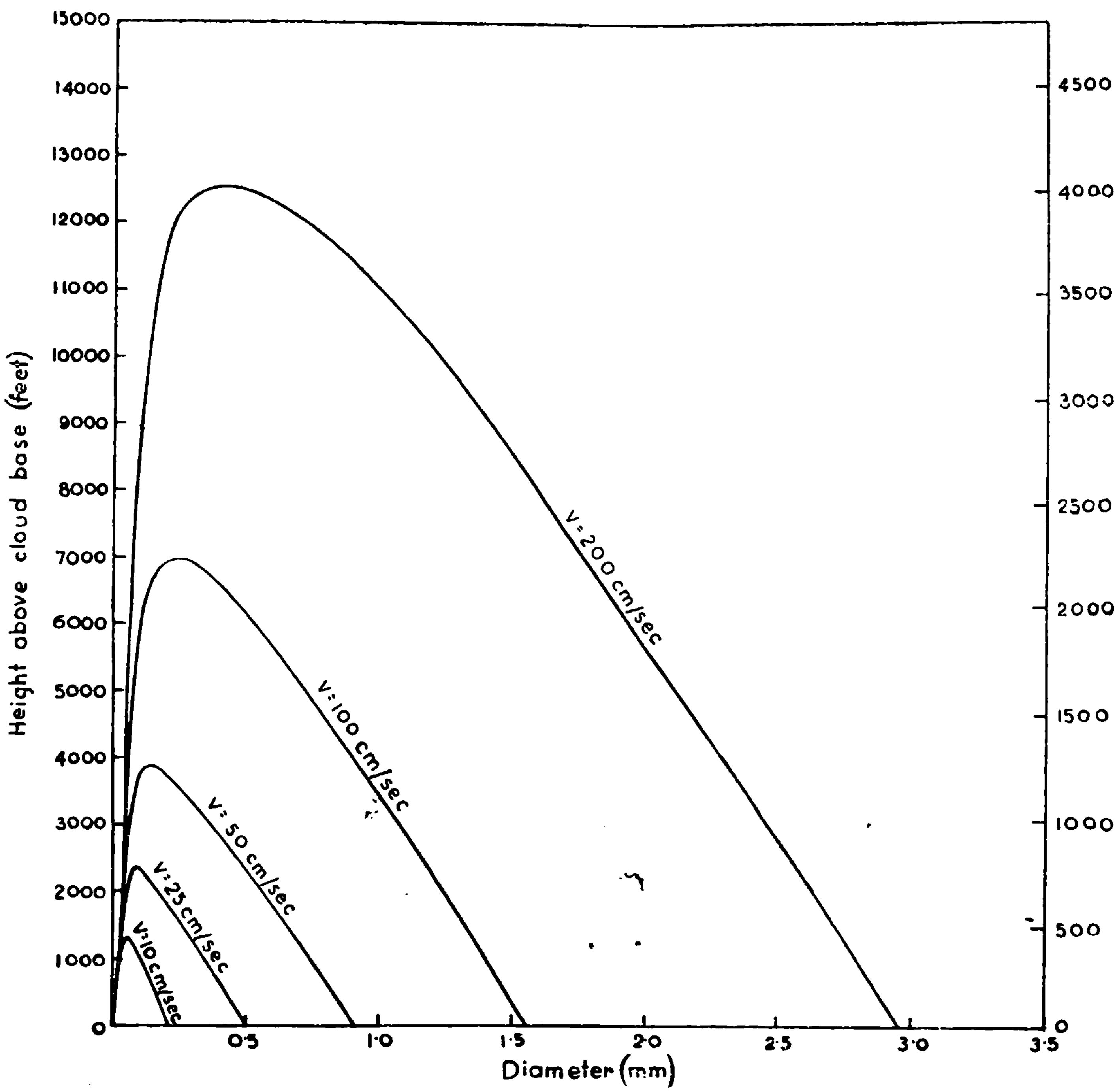


Fig. 4. The changes of drop diameter with height under the conditions specified in Fig. 3.

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radar echoes have the same column structure and show no increase in intensity around freezing level ; certainly in the first two examples the rain formed without ice crystals being involved, while in the last it is clear that heavy rain was falling before there was evidence of glaciation. It appears therefore that the rain formed entirely from the liquid and the vapour phase, that is, either by the condensation process or by the coalescence of water droplets. It is well known that, although cloud droplets form initially by condensation, they would require times of the order of 20 or 30 hours to grow to the size of raindrops. The remaining process by which they can form is coalescence of cloud droplets, and it is of interest to investigate the rate of growth by this process.

This has been done in detail by the author[13], who on a number of simplifying assumptions, showed that the rate of growth by coalescence in a cloud of average characteristics was sufficient to give rise to raindrops greater than 1 mm. in diameter from clouds 5,000 to 10,000 feet thick, provided there was an upward air current of the order of 2 or 3 feet per second. The method of calculation's allowed the trajectories of raindrops growing in this way to be determined as a function of the supersaturation in the cloud, the cloud water content, vertical air velocity, etc. A series of curves was obtained giving the diameter which the drops would attain, as a function of height above the cloudbase and of time, for different vertical air velocities. These are given in Figures 3 and 4. The general conclusion drawn from these calculations was that the coalescence process is capable of accounting for raindrops of a wide range of sizes and can therefore be the mechanism at work when rain forms in non-freezing clouds.

One interesting deduction which can be made from calculations of this kind is as follows. If we consider only those drops which are moving downward relative to the ground, and if n is the number of raindrops of given size falling through unit area per second, then N, the number of raindrops per unit volume at any level, is given by

$$N = \frac{n}{v - u}$$

where v = vertical air velocity in the cloud

u = terminal velocity of the drops

This clearly increases upward from the base of the cloud and tends to infinity at the top of the trajectories. Numerical values of drop density have been calculated for a cloud with an upward air velocity of 100 cm./sec. and a cloud water content of 1 gm./cubic metre, giving the curve shown in Figure 5. In the same way, the rain water content at any level is given by $\frac{\pi ND^3}{6}$ and this has also been computed in terms of n, giving the values shown in Figure 5.

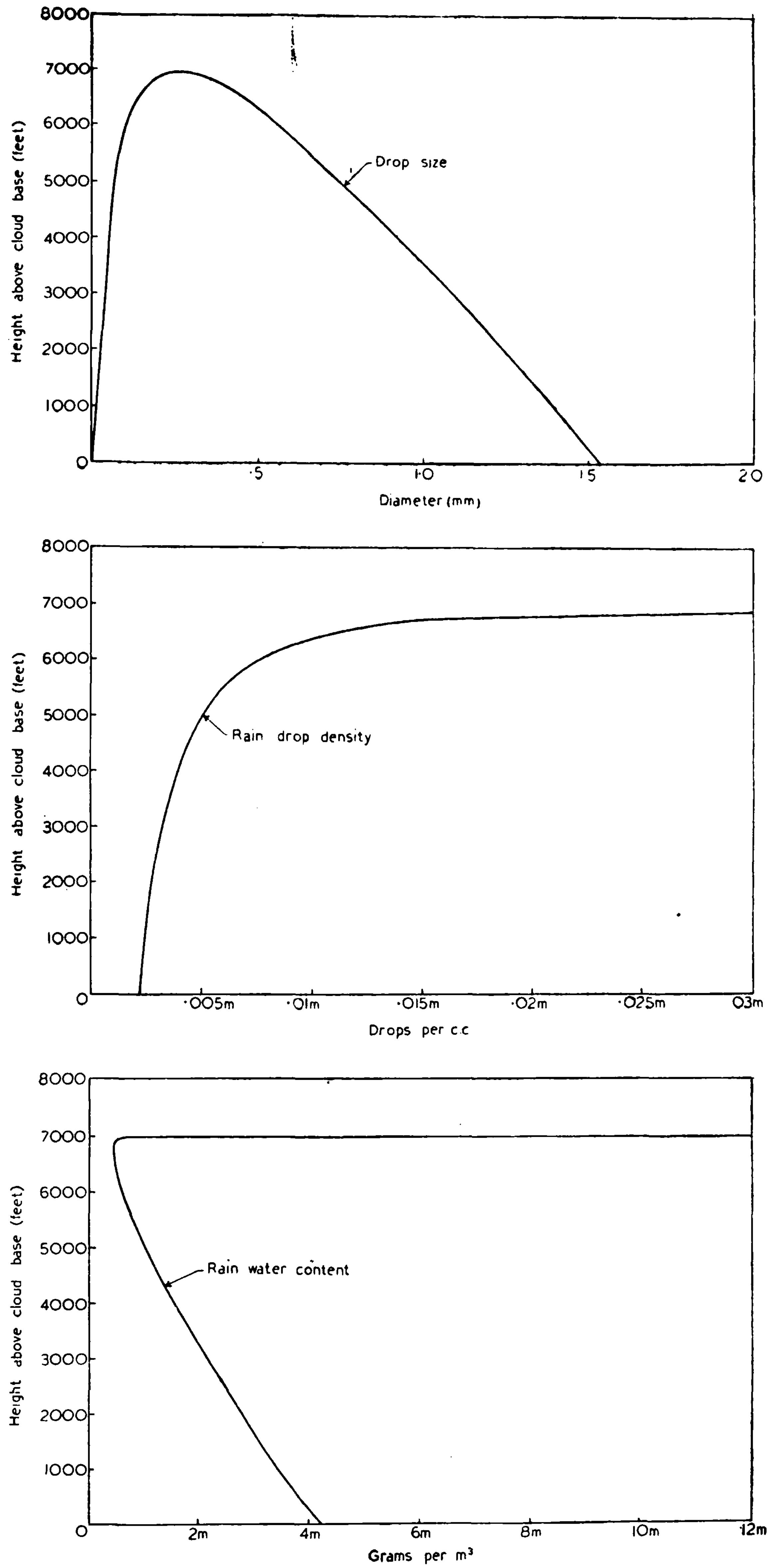


Fig. 5. Theoretical prediction of the variation with height of drop diameter, drop density and rain water content for the cloud conditions specified in Fig. 3.

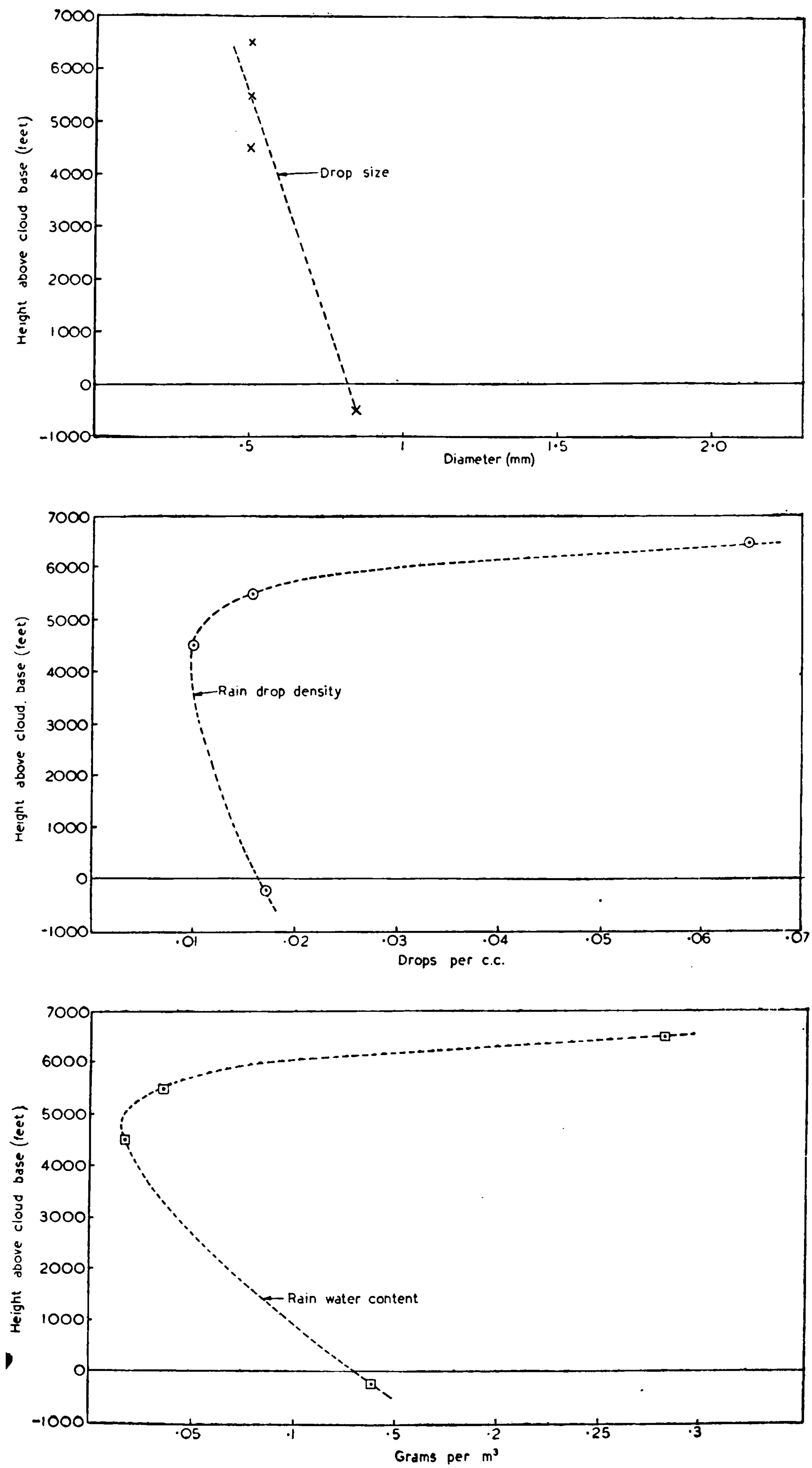


Fig. 6. Experimental observations of the variation with height of drop diameter, drop density and rain water content, made by Smith on a non-freezing cloud on June 1st, 1948.

Because of the assumption that all the drops have identical trajectories, drops of one size appear to be concentrated in a region of infinitesimal width and the rain water content appears to be infinite. In practice, the trajectories are unlikely to coincide exactly and the region would have finite width and finite water content.

It would be expected from these calculations that, if a cloud were producing rain by the coalescence process and the raindrop trajectories tended to coincide, a concentration of water drops or a great increase in rain water content would occur at some height above the cloud base.

This result has been verified in a qualitative fashion by the fact that, in flying at different heights through non-freezing clouds which are producing rain, it is frequently found that there is a region of high rain water content in the upper half of the cloud. In addition, in an early investigation of non-freezing clouds, Smith[7] was able to make measurements of drop size, drop density and rainwater content at a variety of levels.

His observations are shown graphically in Figure 6 and it is seen that they are in remarkable agreement with the theoretical curves of Figure 5. It may be concluded, therefore, that there is strong reason for supposing that coalescence plays an important part in the formation of rain in non-freezing clouds. By analogy, it is also highly probable that the coalescence process is at work in convective clouds which build up above freezing level but remain in the supercooled state.

From radar observations of rain from different types of cloud and from flight observations made in the clouds, the general conclusion can be reached that there are at least two mechanisms by which rain forms. The first of these is the Bergeron process in which rain follows the appearance of ice particles in the upper part of supercooled clouds. The radar echo obtained on these occasions is characterised by the appearance of an intense radar band just below freezing level, due to the melting of ice particles or snow flakes as they cross the 0° isotherm. It is also found that other radar bands sometimes appear in the atmosphere at heights where the temperature is about − 16°C. The behaviour of these bands is consistent with their having formed by the spontaneous freezing of water drops in the cloud.

The second mechanism leading to rain formation occurs in non-freezing clouds of the convective type and in convective clouds which extend above freezing level. The process involves only water drops and it is found that coalescence of cloud droplets plays an important part in it.

II—ARTIFICIAL RAINMAKING

Introduction

The artificial production of rain has received a great deal of prominence in the literature since 1946 but interest in the subject goes back to very much earlier periods. One of the earliest suggestions of the possibility of rainmaking by introducing cold materials into a cloud was that of Gathmann[14], who took out a patent for the production of rain by seeding clouds with "liquid carbonic acid" in 1891. It was advocated that tests of this character be carried out but there is no record of it having been done. In 1904 we find that Gregory suggested a similar process at the Tenth Meeting of the Australian Association for the Advancement of Science[15], using liquid air instead of carbon dioxide. It was not until 1930 that actual experiments of this kind were carried out. These were performed from aircraft by Veraart in Holland[16], but the results he obtained were not clear-cut and interest in the subject lapsed.

The subject was revived in dramatic fashion in 1946 when Schaefer[17] showed that dry ice or solid carbon dioxide pellets were very effective in inducing ice crystals to form in a cloud of supercooled droplets in a cold chamber in the laboratory. Shortly afterwards he permormed an experiment in the free atmosphere in which a fairly large stratiform cloud of supercooled droplets was transformed to ice particles when seeded with about 10 pounds of dry ice.

This was soon followed by experiments in Australia in which the first properly authenticated fall of rain to the ground was produced by the dry ice process in February 1947. In this experiment[18] 300 pounds of dry ice were dropped into a cumulus cloud 12,000 feet thick, west of Sydney, New South Wales. The temperature at the top of the cloud was approximately $-8°C.$ and after seeding, a fall of rain totalling between $\frac{1}{4}$ and $\frac{1}{2}$ inch fell to the ground from the cloud. A great number of experiments of a similar nature have since been performed which leave no doubt whatever that clouds in a suitable condition can be induced to produce substantial quantities of rain by this process.

The basic ideas behind the concept of the artificial production of rainfall are relatively straightforward. For rain to fall naturally it was shown in Part I of this paper that certain critical conditions have to be met. These relate to the cloud water content, the temperature of the cloud, the nature and magnitude of the up-currents, etc. If all the required conditions are met, rain will form naturally. If, on the other hand, one of these conditions is missing, a cloud might be induced to produce rain if it is supplied artificially. Most rainmaking experiments to date have been concerned with supplying only one of the many factors which enter into the rain formation processes, namely, supplying nuclei of a kind appropriate to initiating the rain-forming process. In the case of supercooled clouds, these consist either of ice crystals themselves or freezing nuclei upon which ice crystals can grow. In the case of warm clouds, they consist of large water droplets or, alternatively, large hygroscopic nuclei to initiate growth by coalescence.

An outstanding difficulty in performing weather modification experiments is to determine with certainty weather the effects obtained are due to the introduction of seeding materials or would have occurred in any case. For this reason, seeding experiments, as distinct from operations intended for the production of rain over a widespread area, are preferably performed on one of a group of clouds all of which have similar properties. The behaviour of the treated cloud is then compared with that of surrounding clouds which have not been seeded. Useful information is obtained by visual observation of the treated cloud, but by far the most definitive evidence comes from airborne radar sets. They make it possible to verify with a considerable degree of certainty that there were no precipitation elements in the cloud before seeding took place and to observe the growth of precipitation after the introduction of seeding materials.

It is now proposed to describe in greater detail some of the experiments which have been performed in this field.

Experiments on Supercooled Clouds

(a) Dry Ice Seeding

As already indicated, the production of artificial rain by the dry ice process is based on the Bergeron mechanism of rain formation. As clouds build up in the atmosphere the cloud droplets of which they are composed remain in the supercooled state long after the temperature of the cloud has dropped below freezing level. Ice crystals are unlikely to appear naturally in such clouds until a temperature of about − 15°C. is reached. There are a whole range of clouds, therefore; the temperature of the tops of which might extend from 0°C. to − 15°C., which are unlikely to rain naturally by the Bergeron process but might be induced to produce rain by the artificial introduction of ice crystals.

Perhaps the most direct method of doing this is to drop pellets of dry ice into a cloud from an aircraft. The pellets have a surface temperature of − 80°C. and, in falling, they cool a thin column of air to a temperature below − 40°C., at which a copious supply of minute ice crystals form. These ice crystals diffuse through the cloud and grow rapidly at the expense of the supercooled droplets. The larger ones fall, growing further by accretion as they do so, and ultimately emerge from the base of the cloud as rain.

A typical dry ice experiment[19] was one performed on August 25, 1948 near Bathurst in New South Wales. On this occasion there was alto-cumulus cloud extending from 4,500 feet to 8,000 feet, the temperature at the top being − 7°C.

The aircraft made a run across one cloud cell, approximately three miles wide, and a total of 40 pounds of dry ice was dropped in a single run across the cloud. After nine minutes snow streaks visible for about a mile were seen coming from the bottom of the cloud. Sixteen minutes after the dry ice drop the streaks extended almost to the ground, were very much more intense and were visible from 10 miles. After 19 minutes a snow storm had developed and at this time was reaching the ground. It continued to grow in intensity and area, and covered approximately 50 square miles at the end of 50 minutes. A photograph of the precipitation at this stage is given Plate V. It shows that it consisted of snow which melted just before reaching the ground. Thereafter the cloud began to dissipate and the precipitation ceased after an hour.

The aircraft made several flights through the precipitation, and at the time of greatest intensity it was found to consist of snowflakes varying from two to five millimetres in diameter.

Similar experiments have been performed in which the aircraft was fitted with radar equipment for observing the growth and fall of the precipitation. A typical experiment is shown in the sequence of pictures in Plate VI. The precipitation first appeared seven minutes after seeding, and this grew rapidly and extended through the cloud, reaching the ground after 20 minutes.

A total of some hundreds of such experiments has been performed from which a fairly accurate description can be given of the performance of clouds when seeded with dry ice. The principal results are as follows :

(*a*) The chances of successfully producing rain from a given cloud are critically determined by the cloud top temperature. At temperatures of − 7°C. and colder there is practically a certainty of inducing precipitation. At temperatures between − 7°C. and 0°C. the chances of success fall off progressively, tending to zero at 0°C. At temperatures colder than − 15°C. there is a high probability of clouds producing rain naturally and the results of seeding experiments lose their significance.

(*b*) The time at which precipitation appears at the base of the cloud depends mainly on cloud thickness. The time for the precipitation to appear does, in fact, consist of two parts : a period of about 10 minutes which is required for the ice crystals to form and grow, followed by an additional time of approximately one minute for every 1,000 feet of cloud depth. This latter clearly is related to the rate of fall of the precipitation.

(*c*) A considerable fraction of the precipitation will reach the ground if the thickness of the cloud is equal to or greater than its height above the ground. The precipitation will fail to reach the ground, however, if the height of the cloud base is about twice the cloud thickness.

(*d*) The intensity of the precipitation increases progressively with increasing cloud thickness. In successful experiments the amount of precipitation reaching the ground varies from 0 to ½ inch and the whole of this usually falls within a period of 40 to 60 minutes after seeding.

Under certain very special conditions clouds have been known to blow up as a result of seeding and turn into huge cumulo-nimbus. A good example occurred during an experiment by Kraus and Squires[18] in February 1947. On that occasion a total of 300 pounds of dry ice was dropped into a deep cumulus cloud west of Sydney. After seeding, the seeded cloud grew rapidly as shown in the sequence of pictures in Plate VII and a fully developed anvil formed after about 45 minutes. In the meantime precipitation was observed to form in the cloud, both on the aircraft radar and on the ground radar set. This reached the ground some 20 minutes after seeding and more than ½ inch of rain was recorded.

This behaviour appears to have been due to the release of latent heat during the initial growth of the ice crystals. It has been calculated that this might produce an increase in temperature of as much as ½°C. in the top of the cloud. If the vertical development of the clouds in the region in which the experiment was performed was limited by a slight inversion, this heat energy might be sufficient to cause the cloud to break through the inversion. If the area above was unstable, the seeded cloud would then build up very rapidly as compared with its neighbours and form a cumulo-nimbus. It should be emphasized, however, that this behaviour is the exception rather than the rule and has occurred only on a few occasions.

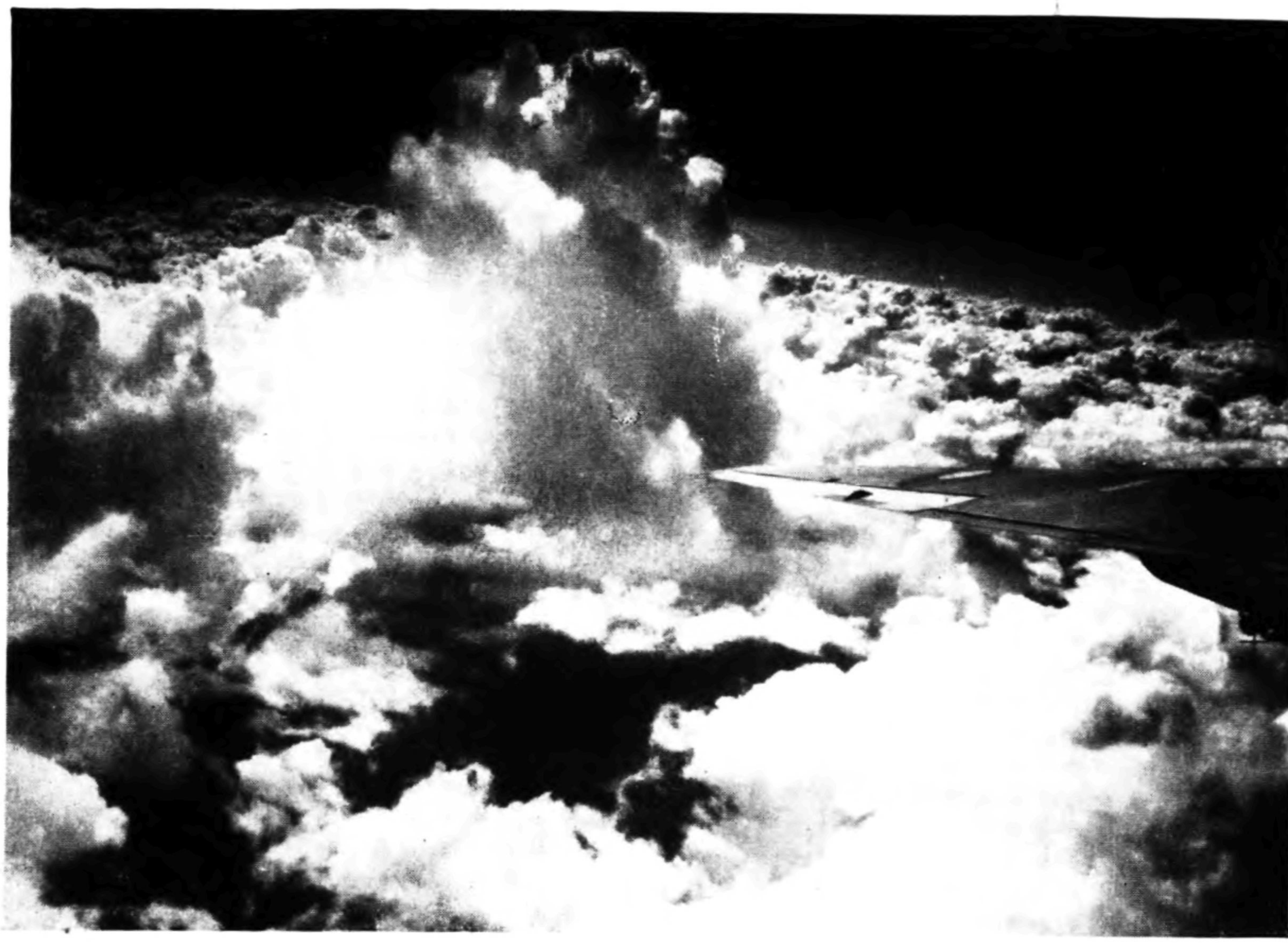
(*b*) *Silver Iodide Seeding*

A great deal of attention has been given in the United States of America to an alternative method of inducing ice crystals to form in supercooled clouds, based on seeding with silver iodide smoke. Silver iodide crystals have the same hexagonal structure as those of ice and very nearly identical lattice dimensions. It was found by Vonnegut[20] that if finely divided silver iodide particles were introduced into a supercooled fog in a laboratory cold chamber, condensation took place upon them and they grew rapidly as ice crystals. This observation led immediately to the suggestion that silver iodide could be used instead of dry ice as a seeding agent in the atmosphere. It was further suggested that since the particles were so finely divided they could be dispensed into the atmosphere from a smoke generator on the ground, on the assumption that the particles would then ascend into appropriate clouds by convective action in the atmosphere.

Since that date there has been tremendous activity, in which silver iodide smoke generators have been operated over wide areas of the United States in an effort

VII(*a*). Blowing up of clouds under special conditions as a result of seeding and eventual turning into cumulo-nimbus. The sequences are shown in plates vii, (*a*), (*b*), (*c*) and (*d*).

VII (*b*)



VII (*c*).

VII (*d*)

to influence the rainfall. Sweeping claims have sometimes been made about the results of such operations but an objective analysis of the results shows that there has been litlle or no effect on the annual rainfall.

Experiments have been performed in Australia in which silver iodide smoke has been dispersed both from aircraft and from ground generators. The results are not by any means as conclusive as those for dry ice but the indications are as follows :

(*a*) In aircraft experiments it appears that much lower cloud temperatures are required before rain is produced. Although the nuclei appear to be effective at temperatures of – 4°C. to – 6°C. in the laboratory, they do not appear to be effective in the free atmosphere until colder temperatures are reached.

(*b*) In the case of seeding from a ground generator, an extensive series of operations was carried out at Hay in New South Wales in the winter of 1951 but no increase in rainfall was obtained which could be ascribed to the seeding operations. In the course of these experiments considerable doubt arose as to whether :

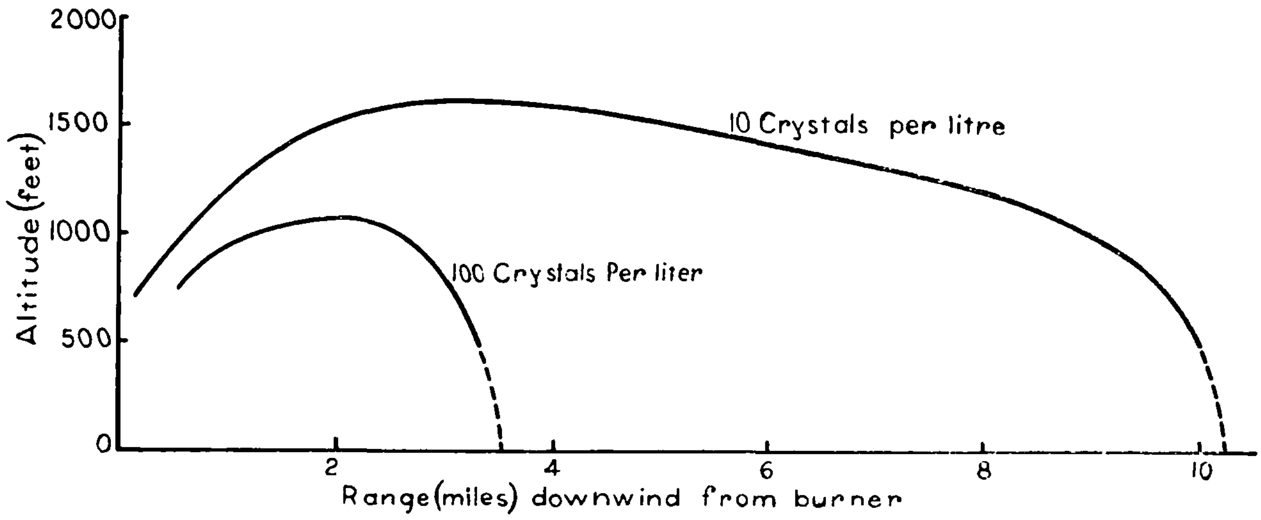
(*i*) The silver iodide smoke ever reached the clouds in question.

(*ii*) If it reached them, whether it was still effective in producing ice crystals.

The experiments of Reynolds and others[21] have shown that the activity of silver iodide is liable to deteriorate rapidly in the atmosphere either as a result of the action of ultra-violet light or of contamination oy a "poison" in the atmosphere.

For this reason, a careful investigation has been made in Australia of the behaviour of silver iodide smoke after it leaves the ground generator. These experiments have been performed by Smith[22], who has designed an airborne cold chamber which is carried in a Dakota aircraft. This aircraft flies at different heights and distances from a ground generator, a sample of air from the silver iodide plume is introduced into the cold box and the number of active ice crystals counted. In this way a measure is obtained of the number and activity of the silver iodide crystals as a function of distance from the source. A typical curve showing the distribution of such particles in a vertical plane downwind from a generator is given in Figure 7. A concentration of the order of 10 nuclei per litre of air is required to produce an effective fall of rain and it is seen from the figure that the concentration is less than this amount at heights above 2,000 feet and at a distance of 10 miles. Clearly, this behaviour on the part of the ground generator is of little or no use for widespread rainmaking. In order to be effective the active plume should reach to heights of the order of 20,000 feet and it is desirable that it should extend to much greater distances.

The measurements have also shown that the decay in activity of silver iodide particles generated in a hydrogen flame can amount to 10^3 or 10^4 times in half an hour, a figure which vitiates this particular method of operation for effective rainmaking. The rate of decay, however, is vitally affected by the mode of



R.P.P.221

Fig. 7. Estimated concentration of ice crystals at —20°C. at various heights and distances downwind from silver iodide generator. Concentration upwind was below detection threshold.

generation of the silver iodide particles and although it is too early to give details, a real hope exists of generating silver iodide particles which do not decay with time.

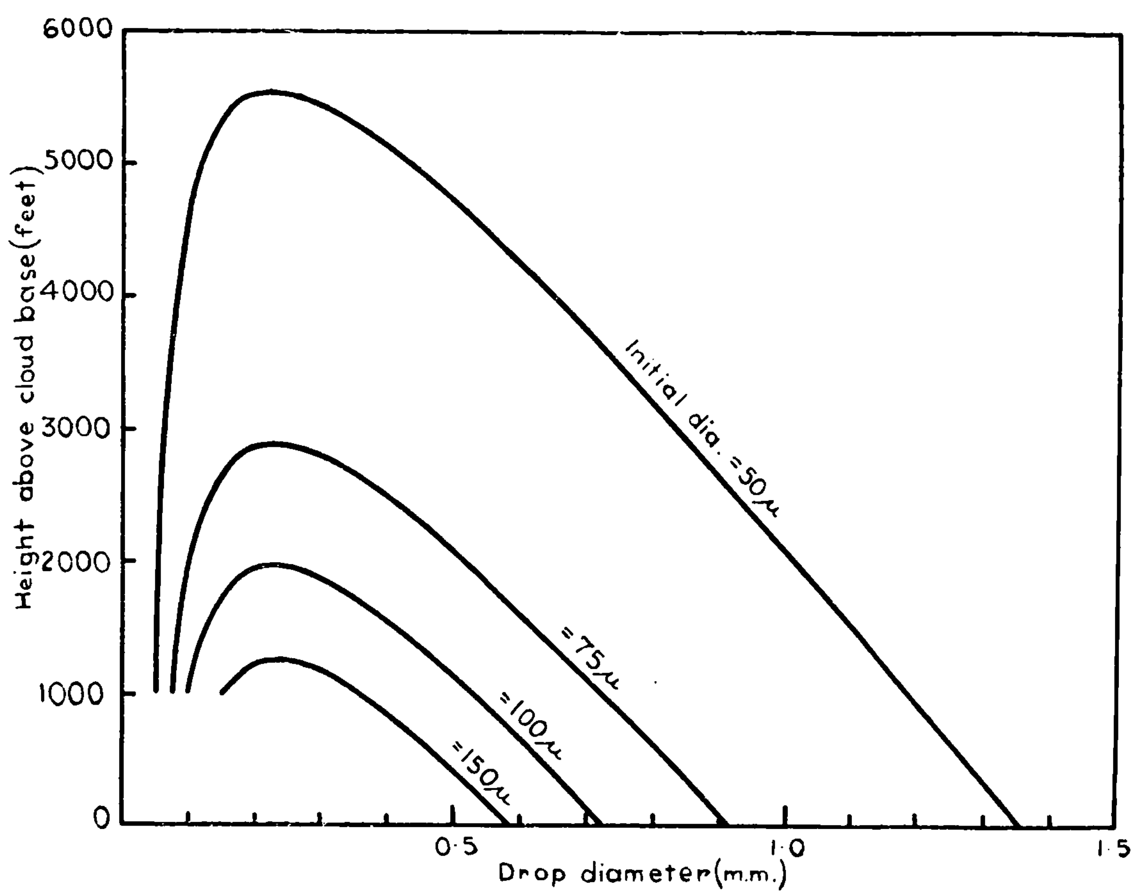
Stimulation of Rain from Warm Clouds

A great deal of the rainfall over the world, particularly that in warmer regions, forms in warm clouds as a result of coalescence of water drops and not from the appearance of ice crystals. Clearly the dry ice or silver iodide process will not induce precipitation in such clouds and it is important to consider alternative methods which will do so. This is particularly true in India where it has been known for many years that coalescence has been the dominant method of rain formation.

It is frequently observed that cumulus clouds will build up to great heights in continental air masses but will not readily produce rain. They are known to have adequate water content and substantial updraughts. The factor which appears to be missing is the existence of a few large cloud droplets at the cloud base or a sufficiently wide distribution of droplet sizes. This deficiency can be overcome in a simple manner by flying through the base of the cloud releasing large water droplets or large hygroscopic nuclei which are capable of starting the coalescence process.

Experiments of this type have been performed in Australia[23]. The preferred cloud conditions are similar to those described for dry ice, but there are two important differences in the procedure. Firstly, the clouds are seeded during their initial growth period, that is, at the time of maximum rate of growth rather than at their maximum size. Secondly, the water drops or hygroscopic particles are released in the cloud base and not in the top of the cloud so that they have an opportunity of growing during both their ascent and descent through the cloud. In practice, water seeding experiments are performed by carrying 600 pounds of water in an external tank and releasing it from spray bars of the type used for agricultural spraying. The water is released at a rate of approximately 100 pounds per mile, so that a track six miles long can be seeded in a single experiment. The optimum drop size is one which is decidedly larger than the droplets already existing in the cloud, but which is still small enough to rise in the updraught within the cloud. Droplet diameter in the region of 50μ to 75μ appear to be a good compromise in this regard.

After being sprayed into the cloud the droplets are carried up in the updraught. Being of greater mass than the cloud droplets, they fall relative to them and pick them up by coalescence. The trajectories of these larger drops can be calculated in the manner of Figure 4 for a given upward air velocity and cloud water content, giving curves similar to those in Figure 8.



R.P.P.22)

Fig. 8. The growth by coalescence of drops sprayed 1000 feet above the base of a cloud having the following characteristics : upward air velocity one metre per second, water content one gram per cubic metre, average cloud-droplet diameter 20μ.

General Assessment of Rainmaking

There can be no doubt from the experiments which have been described, particularly those in relation to dry ice and water seeding, that rain can be induced to fall artificially, sometimes in useful quantities. It does not necessarily follow, however, that rainmaking can now be practised on a large scale with profitable results. There are two main reasons for this. The first is that the cloud conditions suitable for rainmaking are necessarily of a special character and may not occur frequently in any one locality. An analysis of the possibilities in south-east Australia by Smith[24] brings this point out very clearly. The second reason is that the methods which are known to work with certainty depend on the use of load-carrying aircraft capable of flying to great heights. These are expensive to operate with the result that the process is likely to be uneconomical except for very special circumstances. Alternative methods of dispensing seeding material from generators on the ground are not yet a satisfactory substitute. Balloons have been suggested as a possible alternative but it has yet to be shown that they can produce the desired effect.

A great deal more research is required, therefore, before rainmaking is likely to come into existence on a widespread scale. This research needs to be directed in two predominant directions at the present time. The first of these is towards elucidating the many unknowns which still exist in our knowledge of the physics of natural and artificial rain formation. The other would be with the intention of discovering really economic methods of cloud seeding which can be applied with certainty over wide areas.

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